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Review

Exploration of waste cooking oil methyl esters (WCOME) as fuel in compression ignition engines: A critical review

S. Kathirvel [a,*], Apurba Layek [a], S. Muthuraman [b]

[a] *Department of Mechanical Engineering, National Institute of Technology Durgapur, Durgapur, West Bengal, India*
[b] *Department of Mechanical Engineering, Higher College of Technology, Muscat, Oman*

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A B S T R A C T

The ever growing human population and the corresponding economic development of mankind have caused a relentless surge in the energy demand of the world. The fast diminishing fossil fuel reserves and the overdependence of petroleum based fuels have already prompted the world to look for alternate sources of energy to offset the fuel crisis in the future. Waste Cooking Oil Methyl Ester (WCOME) has proven itself as a viable alternate fuel that can be used in Compression Ignition (CI) engines due to its low cost, non-toxicity, biodegradability and renewable nature. It also contributes a minimum amount of net greenhouse gases, such as CO_2, SO_2 and NO emissions to the atmosphere. The main objective of this paper is to focus on the study of the performance, combustion and emission parameters of CI engines using WCOME and to explore the possibility of utilizing WCOME blends with diesel extensively in place of diesel. The production methods used for transesterification play a vital role in the physiochemical properties of the methyl esters produced. Various production intensification technologies such as hydrodynamic cavitation and ultrasonic cavitation were employed to improve the yield of the methyl esters during transesterification. This review includes the study of WCOME from different origins in various types of diesel engines. Most of the studies comply with the decrease in carbon monoxide (CO) emissions and the increase in brake thermal efficiency while using WCOME in CI engines. Many researchers reported slight increase in the emissions of oxides of nitrogen. ANN modeling has been widely used to predict the process variables of the diesel engine while using WCOME. The versatility of ANN modeling was proven by the minimum error percentages of the actual and predicted values of the performance and emission characteristics.

1. Introduction

The search for useful energy and the desire to have a clean and green environment remain always a vital point of interest for any researcher. The fast depleting petroleum reserves have already waved a warning signal all around the globe to look for alternate means to cater to the ever increasing needs of energy. Further, the harmful emissions of fossil fuels also need to be taken care of. Biodiesel made from different renewable sources has become a viable alternative for use as a fuel in Compression Ignition (CI) engines. Biodiesel is referred to as mono-alkyl esters of long chain fatty acids. With the help of a chemical process known as transesterification, the biodiesel is produced from vegetable oils and is used on unmodified compression ignition (CI) engines [1–3]. The variation of the percentage concentration of methyl esters in the biodiesel from different sources leads to considerable changes in the physical and chemical properties of the biodiesel which in turn affects the characteristics of the engine used [4].

Biodiesels from various feedstocks have been tried by different researchers [2,5–12] to study and analyze the performance, emission and combustion characteristics of the CI engine. Encouraging results such as decrease in hydrocarbon (HC) emissions, less pronounced decrease in brake power (BP) and increase in brake specific fuel consumption (BSFC) have been reported. However, the major obstacle in commercializing biodiesel produced from vegetable oil and animal fat is the cost of its production.

Meanwhile, an enormous quantity of used cooking oil is being wasted around the world. Disposal of such oil remains again a matter of concern as many pollution-related problems arise while dumping such stuff in rivers and landfills. This also leads to issues in the maintenance of the ecological balance. The best way to avoid contamination of the waste cooking oil (WCO) is to produce waste cooking oil methyl esters (WCOME) [13–15] and use it as biodiesel in CI engines. Hence, biodiesel produced from waste fried oil or the waste cooking oil is gaining momentum in most parts of the world as a cheaper alternative for pure diesel.

* Corresponding author. Tel.: +919488726288; fax: +919600902364.
E-mail address: kathirnitd@gmail.com (S. Kathirvel).
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Several works using WCOME as the fuel in CI engines have been reported in the literature. Waste cooking oil methyl esters from different origins were used as fuel for diesel engines to study their effects. Kalam et al. [14] experimented with waste cooking oil from two different origins like palm oil and coconut oil with blends of 5% of waste oil and 95% of pure diesel and analyzed the emission and performance characteristics of a 4 cylinder, four stroke, naturally aspirated, indirect ignition diesel engine. Ahmed et al. [16] used Mustard Biodiesel (MB) extracted from waste mustard oil in an inline four-cylinder, Mitsubishi Pajero engine and explored the performance, emission and noise characteristics. Different production technologies employed for methyl ester extraction from the waste oils also influence the performance and emission characteristics of the engines used. Chuah et al. [17] used hydrodynamic cavitation technology to extract methyl esters from palm olein with a high percentage of extraction of more than 96.5% and showed that such intensification technologies make a greater impact in the fuel properties thereby affecting the performance and emission characteristics of the diesel engines.

Even though many reviews [1,18–22] based on the use of biodiesel as a fuel are in existence, a specific review focusing on the use of biodiesel originated from waste cooking oil as the fuel is still missing. This paper is a serious attempt to fill such a gap by critically reviewing the major results of the recent works available in the literature.

2. Waste Cooking Oil Biodiesel

Waste cooking Biodiesel or Waste cooking oil Methyl Ester (WCOME) has all the making of a viable alternate for use in CI engines due to its characteristic to reduce emissions and the scope it extends to alleviate the overdependence on fossil fuels. The physiochemical properties of WCOME are tabulated in Table 1 for comparison. Even though there are many existing methods of producing biodiesel from WCO, Transesterification remains as a popular choice for many researchers. Transesterification is a chemical process in which organically derived oils (vegetable oils, animal fats and recycled waste cooking or frying oils) are combined with alcohol to form fatty esters such as methyl/ethyl esters. Transesterification reaction, also known as alcoholysis, is based on one mole of triglyceride reacting with three moles of methanol to produce three moles of methyl ester, which is known as biodiesel. The Transesterification process is normally carried out with some catalysts to improve the reaction rate and yield. In some cases, catalyst free process is also employed. The catalyst can be alkaline or acidic or may be homogeneous or heterogeneous based on its nature. Problems like separation of products from reactants and formation of soap that shoot up the operating cost of the process are some facts that act against using homogenous catalysts, whereas nonformation of soap and easier separation methods help heterogeneous catalysts to become more popular for the transesterification process [23,24].

Alkali metals supported by the silica of Rice Husk Ash (RHA) can also be used as catalysts for the transesterification process.

Table 1
Comparison of WCOME properties with diesel.

Sl no.	Fuel properties	Diesel	Biodiesel
1	Fuel standard	ASTM D 975	ASTM D 6751
2	Fuel composition	C_{10-21} HC	C_{12-22}FAME
3	Lower heating value (MJ/kg)	42.49	39.6
4	Kinematic viscosity(CST) at 30 °C	4.59	1.9–6.0
5	Density at 15 °C (kg/m^3)	840	880
6	Flash point (°C)	52–96	273
7	Cetane number	45	37
8	Auto ignition temperature (°C)	260	300

Hindryawati et al. [25] used silica of rice husk ash as a supporting material for alkali metals such as Lithium (Li), Sodium (Na) and Potassium (K) to examine the reaction parameters like the amount of catalyst added, duration of reaction, molar ratio of methanol to oil and the reaction temperature. The author successfully applied the impregnation of alkali metals in silica and reported that the catalyst can be reused again for six times as it was proven very easy to separate the catalyst from the reaction solution.

A lot of researchers have explored different production methods to study the impact of different critical parameters of the reaction. Amani et al. [26] investigated the potential of using Cesium impregnated silica as the heterogeneous catalyst for the transesterification reaction of waste cooking palm oil (WCPO) and palm oil (PO). The author used various combinations of Cesium loadings, the methanol-to-oil molar ratios, catalyst loading, reaction time and water content to study their influence on the process variables of the reaction. Detailed characterization of the catalyst was carried out by the authors and 25% of cesium on silica was reported to result in a maximum yield of 90% within a short reaction time of 3 hours at 65 °C with 3 wt % of catalyst loading.

Sneha et al. [27] synthesized a heterogeneous catalyst of 25% Potassium Bromide impregnated in CaO using wet impregnation method for the transesterification process. Fourier Transform Infrared spectrometry (FTIR), X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) techniques were used for the characterization of the catalyst, and Gas Chromatography–Mass Spectrometry (GC–MS) was used to ascertain the composition of the methyl esters formed. The author varied the process parameters of the transesterification method like catalyst loading, reaction time, and methanol to oil molar ratio to analyze their effect in the yield of the methyl esters with the help of Response Surface Modeling (RSM). The transesterified biodiesel was used in a four stroke, direct injection diesel engine with different blends. Less emission was observed for B10 and B20 blends while the brake thermal efficiency increased compared to the pure diesel.

Mechanical stirring methods are handicapped by the long reaction time and lower yield efficiency due to the mass transfer resistance of the immiscible reactants. Hence, many intensification technologies were experimented in the conversion of methyl esters from waste oils of different origins. Microwave assisted intensification [28], hydrodynamic cavitation (HC) [17], ultrasonic cavitation [29] etc., are some of the methods tried by various researchers. Gupta et al. [30] explored the impact of the process parameters of the transesterification reaction using calcium diglyceroxide (CaDG) as a heterogeneous catalyst. The ultrasonic irradiation was used to intensify the reaction, and the parameters like reaction temperature, catalyst loading, methanol to oil molar ratio, ultrasonic and duty cycle on the progress of the reaction were varied to determine the optimum set of variables. Methanol to oil molar ratio of 9:1, catalyst loading of 1% (w/w) of waste cooking oil, reaction temperature of 60 °C, low intensity ultrasonic power of 120 W and 50% duty cycle were found as optimal conditions for the reaction and a maximum biodiesel yield of 93.5% was reported. The conventional stirring method was also compared with the ultrasonic assisted reaction process, and the improvement of the resultant biodiesel properties was highlighted.

Chuah et al. [31] examined the conversion of methyl esters from waste cooking oil from palm olein and refined cooking oil using hydrodynamic cavitation technology. The author studied the impact of the inlet pressure and the geometry of the orifice plate on the yield % and the reaction time of the conversion process. It was reported that 8 times more energy efficiency and 6 times less reaction time were achieved with the optimized orifice plate geometry that had 21 holes for each 1 mm diameter.

The effect of the major operating parameters in methyl ester conversion with hydrodynamic cavitation was further analyzed by Chuah

Table 2
Summary of works on production of WCOME by transesterification process using different technologies.

Author and Year	Oil	Catalyst used	Technology used	Yield	Reaction temperature (°C)	Molar ratio	Reaction time	Key points to note
Amani et al. (2014) [26]	Waste cooking palm oil (WCPO) and palm oil (PO)	Cesium – Modified Silica (CsM-SiO2) as a heterogeneous catalyst	Conventional method	90%	65 °C	20:1	3 hours	• Cesium – modified silica was used as a heterogeneous catalyst. • 25% of cesium on silica was reported to result in a maximum yield of 90% within a short reaction time of 3 hours at 65 °C with 3 wt % of catalyst loading. • The reusability of the catalyst was tested and it was reported that the catalyst can be recycled up to four cycles.
Chuah et al. (2016) [31]	Waste cooking oil (WCO) from palm olein	1 wt.% Potassium Hydroxide as alkali catalyst	Conventional method	97%	60 °C	6:1	90 minutes	• Conventional mechanical stirring is compared with an intensification technology like HC. • Orifice plate geometry and inlet pressure are varied to study yield efficiency and reaction time. • Higher cavitation, generated with multiple holes with less diameter led to more yield efficiency in reduced reaction time.
			Hydrodynamic cavitation	98%			15 minutes	
	Refined cooking oil		Conventional method	97%			90 minutes	
			Hydrodynamic cavitation	98%			15 minutes	
Chuah et al. (2015) [32]	Waste cooking oil (WCO) from palm olein	1 wt.% Potassium Hydroxide as alkali catalyst	Conventional and Hydrodynamic cavitation technology	Not less than 98.5%	60 °C	6:1	15 minutes	• Oil to methanol molar ratio (1:4–1:7), reaction temperature (50–65 °C) and catalyst loading concentration (0.5–1.25 wt%) were varied to determine the optimum value.
Sneha et al. (2015) [27]	Waste Cooking Oil from restaurants	25% KBr impregnated in CaO	Solid Catalyst	78.9% max.	65 °C	9:1 to 12:1	1 to 3 hours	• Solid heterogeneous catalyst of KBr/Cao was used. • Catalyst was characterized by Fourier Transform Infrared spectrometry (FTIR), X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) techniques. • RSM was used to optimize and determine the optimum process conditions. • Molar ratio of 12:1, 3% of catalyst loading and a reaction time of 1.8 hours were found as optimum. • Engine tests were conducted and BTE was reported to increase while BSFC decreased with increase in load. • Emission profile showed promising features of less hydrocarbon, carbon monoxide and particulate matter emissions.
Gupta et al. (2015) [30]	Waste Cooking Oil from restaurants	Calcium Diglyceroxide (CaDG) as a heterogeneous catalyst	Intensification by Ultrasonic Irradiation	93.50%	60 °C	9:1	30 minutes	• Transesterification of WCO using CaDG as a heterogeneous catalyst under the influence of Ultrasonic irradiation. • Reaction temperature (45 to 65 °C), catalyst loading (0.5–1.25% (w/w) of WCO), methanol to oil molar ratio (6:1, 9:1, 12:1 and 14:1), ultrasonic power (60 W to 120 W) and duty cycle on the progress of the reaction were varied to determine the optimum set of variables. • Methanol to oil molar ratio of 9:1, catalyst loading of 1% (w/w) of waste cooking oil, reaction temperature of 60 °C, low intensity ultrasonic power of 120 W and 50% duty cycle were found as optimal conditions for the reaction and a maximum biodiesel yield of 93.5% was reported.

et al. [32] Oil to methanol molar ratio, catalyst loading and reaction temperature were varied, and the role of their variations on yield efficiency was studied. Higher molar ratio of 1:6, optimum catalyst loading of 1% KOH and an optimum reaction temperature of 60 °C were proven to exhibit good results.

Various other technologies like Low Temperature Conversion Process (LTC), Hydrothermal Conversion Process (HTC), Hydrothermal Liquefaction Process (HTL) and Catalytic Hydrogenation (HDO) are also fast emerging to minimize certain limitations of the above discussed catalytic transesterification processes [23]. Table 2 provides the major abstract of the above review on different production methods of transesterification.

3. Work on the study of performance, emission and combustion characteristics

Several investigations on the study of performance, emission and combustion characteristics while using waste cooking oil biodiesel have been studied and discussed in this section. Table 3 shows the summary of the type of fuel tested, engine used and trends noticed for waste cooking oil biodiesel done by different investigators.

Muralidharan et al. [33] conducted experiments on a single cylinder four stroke variable compression ratio CI Engine fueled by waste cooking oil and its blends with standard diesel to evaluate the performance, emission and combustion characteristics. Fuel blends of 20%, 40%, 60% and 80% were used at a compression ratio of 21 with an engine speed of 1500 rpm for different loading conditions. It was observed that the brake thermal efficiency of the blend B40 increased with the increase in applied load but the exhaust gas temperature decreased with the increase in load. At higher loads, the HC emission was also increased. Biodiesel from different origins has some common properties like lower heating value and high viscosity and density. This can be reflected while measuring the core parameters. To highlight this fact, two different varieties of biodiesel, namely, Canola Oil Methyl Esters (COME) and Waste Palm Oil Methyl Esters (WPOME) were used as fuel by Ozsezen and Canakci [34] who carried out experiments on a 6 cylinder, water cooled, naturally aspirated, direct ignition Diesel Engine to analyze the performance, combustion and emission characteristics of the engine working at full load conditions with constant speeds of 1000, 1250, 1500, 1750 and 2000 rpm. It is concluded that due to lower heating value of the BD, the brake power achieved using COME and WPOME was less than that of Petroleum-Based Diesel Fuel (PBDF). The HC, CO, CO_2 and smoke opacity got reduced for both the kinds of biodiesel while NOx emissions increased due to higher cylinder temperatures caused by shorter Ignition Delay.

The impact on the performance and emission characteristics of two DI four stroke Diesel Engine Generators of different specifications fueled by Diesel and WCO-Diesel Blends was investigated [35]. The authors conducted experiments on a Yanmar YDG-5500 generator with an L100 air-cooled single-cylinder engine, and on a Kubota GL-7000 generator with a Z482 liquid-cooled two-cylinder engine, and the authors concluded that unburned HC emissions were affected by the nature of the fuel used irrespective of the engine and its operating conditions, whereas emissions and the exhaust gas temperature were dependent on the engine conditions rather than the fuel used.

One of the major findings in the emission analysis of WCOME fueled CI engines for many researchers is that the harmful NOx emissions normally increased compared with Petro diesel as fuel. There are several methods to offset this characteristic that is commonly referred to as *biodiesel NOx effect*. Exhaust Gas Recirculation (EGR) is one of the useful modifications that is meant to reduce the NOx emissions of a biodiesel driven CI engine. The combustion and emission characteristics of a four-cylinder direct injection diesel engine with treated waste cooking oil blended with ordinary diesel as the fuel were analyzed employing an external EGR system [36]. The results were compared with the characteristics with ordinary diesel. Because of the advanced injection timing caused by the higher bulk modulus of the TWCO (Treated Waste Cooking Oil) blend, the NOx emissions increased whereas the same got reduced when EGR is employed in the engine set up. The reduction in oxygen content due to EGR was quoted as the reason for the above phenomena.

Normally, most of the studies with waste cooking oil methyl esters were carried out under steady state conditions. Lin et al. [37] tested Ultra Low Sulfur Diesel (ULSD) with WCOME on the Heavy Duty Diesel Engine (HDDE) under the US-HDD transient cycle. The authors analyzed the complete emission profile of a heavy duty Diesel engine, and reported that due to better combustion efficiency of the WCOB blends, PAH emissions were decreased by 7.53%–37.5% while HC emissions were reduced by 10.5%–36.0%. Particulate Matter (PM) emissions registered a decrease of 5.29%–8.32% and the reduction in CO emissions was recorded as 3.33%–13.1%.

Waste cooking oil derived from palm oil and coconut oil was blended with pure diesel in the proportion of 5% WCOME and 95% pure diesel and was used in a multi-cylinder vertical diesel engine [14]. The lower heating values of palm oil and coconut oil reduce the brake power by 0.7% for C5 and 1.2% for P5 blends as compared to pure diesel. Due to the presence of 92% of highly saturated fatty acids in coconut oil compared with that of 50% of palm oil, the exhaust temperature is 1.12% higher for P5 while it is 1.58% for C5. Further, lower Co emission and higher CO_2 emissions were recorded for P5 blends whereas lower HC emissions were registered for C5. NOx emissions were reduced by 1% for C5 blend and increased by 2% for P5 blend.

Lower calorific value, higher viscosity, lower volatility of waste fried oil and the presence of more oxygen molecules in the fuel rightly decides the performance and emission parameters. Hirkude and Padalkar [38] thoroughly investigated the same, working on a single cylinder four-stroke DI diesel engine with blends of Waste Fried Oil Methyl Esters (WFOME) and comparing the performance and emission characteristics with that of mineral diesel. An increase in BSFC of 6.89% and a decrease in BTE of 6.5% were observed by the authors for B50 blend at rated output. With reference to the emissions, 21%–45% reductions in CO emissions 23%–47% reduction in the particulate matter were also found for different blends.

Experiments were conducted for different loading conditions such as 25%, 50% and 100% at different speeds of 800 rpm, 1200 rpm, 2400 rpm and 3600 rpm on a EURO IV Diesel Engine with pure diesel and WCO biodiesel blends by An et al. [4] who analyzed the variation of performance, emission and combustion characteristics of the above tests and reported lower HC as well as lower NOx emissions for the biodiesel blends. The BSFC was recorded as higher at partial loads and at low speeds. BTE was recorded as higher at 50% and 100% loads while it was less for 25% load condition.

Two different categories of biodiesels such as virgin vegetable oil biodiesel and waste oil biodiesel were studied on a four cylinder 4 stroke water-cooled turbocharged DI engine [39]. The authors came up with similar results for both the types of biodiesel studied. With biodiesel, 15% higher BSFC and slightly higher in-cylinder pressure and heat release rates were recorded which is on par with the other works in the literature. The performance, emission and combustion characteristics of a constant speed single cylinder 4 stroke air cooled DI diesel engine using various blends of waste cooking oil methyl esters as its fuel have been reported by Nantha Gopal et al. [40]. Experiments were carried out using blends of WCOME with mineral diesel in different proportions such as 20%, 40%, 80% and 100% and were compared with that of a diesel. Increase in specific fuel consumption, Decreased HC, CO emissions, Decreased BTE and increased NOx emissions were observed while using WCOME as the fuel as compared with diesel. WCO emulsion, made up of mixture of 70% WCO, 15% water, 10% ethanol and 5% surfactant, is another option attempted in Reference [41]. The authors have used neat waste cooking oil (WCO), WCO Emulsion and mineral diesel as fuel in a four stroke water cooled naturally aspirated single cylinder Kirloskar – AVI – CI engine and studied its performance, emission and combustion characteristics. Based on the experimental results, neat WCO resulted in higher smoke, hydrocarbon emissions and carbon monoxide emissions when compared with neat diesel. Authors also found that all emissions were considerably reduced while using WCO emulsions. At high power outputs, WCO emulsion results in higher cylinder peak pressure and maximum rate of pressure rise compared to neat WCO. Results demonstrate that smoke, HC and CO emissions increased with neat WCO and also the ignition delay was higher with neat WCO and its emulsion. It was revealed that the performance of diesel engines fueled with WCO emulsion without any modifications was on par with that of diesel engine.

Table 3
Summary of works on study of performance, combustion and emission characteristics of CI engines with WCOME as fuel.

Author (year)	Fuel tested	Engine USED	Trends noticed
Muralidharan et al. (2011) [33]	• WCO Diesel Blends • B20, B40, B60, B80 and B100	4-Stroke, water cooled, variable compression ratio compression ignition engine	• Increase in brake thermal efficiency recorded for all blends with the increase in load. • Brake power decreases with increase in biodiesel content. • Steady increase in mechanical efficiency and decrease in SFC recorded as the load is increased. • Longer ignition delay leading to higher combustion pressure. • Slight increase in NOx but still comparable with that of diesel.
Ozsezen and Canakci (2011) [34]	• COME (CANOLA OIL Methyl Esters) • WPOME (Waste Palm Oil Methyl Esters) • PBDF (Petroleum based Diesel Fuel)	Four stroke, 6 cylindered, water cooled, NA, DI Diesel Engine	• Due to lower heating value of BD, the maximum power output got decreased with BD. • Because of the early injection timing and shorter ID, the start of combustion (SOC) was advanced for BD. This fact increased the peak cylinder pressure and temperature leading to an increase in NOx emissions. • Lower HC, CO, CO_2 and smoke opacity were observed for BD. • 11% and 22% increase in NOx emission compared to pure diesel, were reported for WCOME and COME blends when running in full load conditions.
Yilmaz and Morton (2011) [35]	• WCO • B0 • B20 • B100	Two DI Diesel Engines with different CRs (20:1 and 23.5:1), different cooling systems (air and liquid cooled) and with different number of cylinders (single and twin).	• BTE increases for BD blend irrespective of the engine type. • Higher Exhaust Gas Temperature was observed for BD compared with Diesel in the engine with lower CR whereas there was nearly no change while operating in the engine with higher CR. • Irrespective of the engine type, O_2 and CO emissions decreased when load was increased. • Remarkable reduction of UHC emissions was observed in both the engines with BD. • The trend of NOx emissions varies considerably with different engines, fuels and operating conditions. Increase in load increases the NO emissions for both the engines.
Abu-Jrai et al. (2011) [36]	• Treated Waste Cooking Oil Biodiesel – TWCO50 • Conventional Diesel	Four cylinder "TEMPEST" WC, NA, DI diesel Engine with external EGR	• Higher cetane number of TWCO(=49) led to shorter ID • Due to higher bulk modulus of compressibility of the TWCO blend, the injection timing got advanced and that led to lower smoke and HC emissions whereas NOx got increased. • BSFC for TWCO blend was reduced due to lower heating value of the blend. • When running with TWCO 50 oil, NOx emissions were reduced by 37%, 29%, 22% for the low, medium and high loads of operation whereas the NOx emissions were reduced further when 50% EGR was used. The emissions were 40%, 47.5% and 55% when used with 50% EGR.
Lin et al. (2011) [37]	Ultra-Low Sulfur Diesel (ULSD) blended with • WCOB5 • WCOB10 • WCOB20 • WCOB30	6 cylinder, Cummins Direct Injection Heavy Duty Diesel Engine(HDDE) under the US-HDD transient cycle test conditions	• BSFC increased with increasing WCOB blends. • WCOB blends improve combustion efficiency and hence there is a decrease in PAH emissions, HC, CO and PM.
Kalam et al. (2011) [14]	WCO from Palm oil and Coconut Oil • P5 • C5 • B0	Multi-cylinder four stroke diesel engine	• Reduced brake power with both P5 and C5 blends of WCO • Decreased HC and CO emissions compared to pure diesel (B0) • NOx emissions reduced by 1% for C5 blend and increased by 2% for P5 blend. • Due to shorter ignition delay of coconut oils, the smoke emissions of C5 are less compared to P5 and B0.
Hirkude and Padalkar (2012) [38]	Waste Fried Oil Methyl Esters (WFOME) • B50 • B90 • B100	Single cylinder four stroke direct injection diesel engine	• BSFC increased as the blend of WFOME is increased. • Increase in Exhaust Gas Temperature. • Sulfur Oxides, CO and Particulate Matter reduced with WFOME as fuel. • Increase in NOx emission with the increase in WFOME concentration in the blend noticed. • NOx emission increased by 4%, 7%, 9% and 10% for B50, B70, B90 and B100 blends respectively.
An et al. (2013) [4]	• Pure Diesel • WCO Blends – B10 • B50 • B100	In-line 4 cylinder four stroke Turbocharged DI diesel Engine supported by a Common Rail Injection System	• BSFC is higher particularly at low engine speed and partial load conditions. • Slightly higher BTE at 50% and 100% loads but poor BTE at low loads. • Slightly shorter Ignition Delay for WCO Blends. • Lower Peak Heat Release rate and Reduced HC emissions recorded. • NOx Emissions got reduced for B100 compared to pure diesel.
Tesfa et al. (2013) [39]	• WOB (Waste Oil Biodiesel) • ROB (Rapeseed Oil Biodiesel) • COB (Corn Oil Biodiesel) • Normal Diesel	4 cylinder 4 stroke Direct Injection and turbocharged water cooled Diesel Engine	• Higher Peak cylinder pressure and HRR observed for Biodiesel Blends. • Advanced Ignition Delay for Biodiesel. • Increase in BSFC for BD at all load conditions.
Nantha Gopal et al. (2014) [40]	• WCME 20 • WCME 40 • WCME 80 and • WCME 100	Constant Speed single cylinder 4 stroke air cooled Direct Injection CI Engine	• Higher SFC for WCME fuels under different loading conditions. • Decreasing trend of SEC when the load is increased for WCME fuels. • Slightly Lower BTE, Lower HC and CO Emissions. • Increased NOx Emissions and smoke content for WCME fuel blends. • 18.33% higher NOx emissions were reported at full load for WCME 100 as compared with the Diesel fuel. • Similar cylinder gas Pressure trends to that of diesel for WCME blends.
Senthil Kumar and Jaikumar (2014) [41]	• Pure Diesel • WCO • WCO Emulsion (Consisting of 70% WCO, 15% water, 10% Ethanol and 5% Surfactant)	4 stroke, water cooled, Naturally Aspirated single cylinder Kirloskar – AVI – CI engine	• Increase in BTE for WCO emulsions while WCO recorded the lowest BTE when compared with mineral Diesel. • Increase in Peak Pressure for WCO Emulsions at high power outputs whereas at low power outputs, WCO emulsions exhibited reduced peak pressure. • Ignition delay was reduced with increasing power outputs for all fuels tested. • NO reduced with neat WCO while the lowest NO emission was recorded for WCO emulsion. • Higher CO emissions while using WCO emulsion than WCO at low power outputs while WCO emulsion recorded lower CO emissions at higher power outputs. • Nearly 24% decrease in NOx emissions were observed while running with WCO as fuel as compared with neat diesel. At maximum power output conditions, NOx emissions decrease from 820 ppm to 620 ppm with WCO as fuel.
Ahmed et al. (2014) [16]	WCO from Mustard Oil • MB 10 • MB 20 • PB 10 • PB 20 • B 0	Multi-cylinder Mitsubishi Pajero engine	• Superior oxidation stability of MB among most of the biodiesel was recorded. • Higher density and lower calorific value of the test fuel reduced the performance whereas both the HC and CO emissions got reduced. • Slight reduction in the noise levels were observed with MB blends. • 9% and 12% increase in NO emissions were reported with MB10 and MB20 blends respectively as compared with neat diesel.
Chuah et al. (2015) [17]	WCOME from Palm Olein • B 10 • B 30 • B 50 • B 0	Inline vertical 6 cylinder Diesel Engine	• Decrease in Engine Torque, brake power and brake thermal efficiency were observed with the WCOME blends. • BSFC and exhaust gas temperature were increased whereas the NOx and CO2 got increased with the test fuel. • On an average, the increase in NOx emissions for B10, B30 and B50 blends were recorded as 4.7%, 10.3%, and 19% respectively as compared with conventional diesel. • Considerable decrease in CO emissions was reported with biodiesel blends.

Table 4
Summary of works on variation of operating parameters of the engine with WCOME as fuel.

Author (year)	Fuel tested	Engine used	Trends noticed
Muralidharan et al. (2011) [33]	4-Stroke, water cooled, variable compression ratio compression ignition engine	• Compression Ratio (18, 19, 20, 21 and 22)	• Longer ignition delay, maximum rate of pressure rise, lower heat release rate and higher mass fraction burned at higher compression ratio for waste cooking oil methyl ester when compared to that of diesel. • Increase in brake thermal efficiency recorded for all blends with the increase in compression ratio. • Brake power decreases at high compression ratios.
Kannan and Anand (2012) [42]	Single cylinder 4 stroke DI KIRLOSKAR diesel engine	• Injection Pressure (220 bar to 300 bar in the interval of 20 bar) • Injection Timing (23° bTDC, 25.5° bTDC and 28° bTDC)	• Increase in BTE for an increase in Injection Pressure as well as for increasing loading conditions. • Lower NOx emission for biodiesel compared to diesel but NOx increases with an increase in injection pressure for biodiesel. • Rise in maximum gas pressure and decrease in ignition delay observed for biodiesel for increasing injection pressure. • HRR increases for biodiesel compared to diesel but at higher injection pressures and advanced injection timings, HRR got reduced. • Ignition Delay does not depend upon injection pressure and injection timing. It reduces for biodiesel when compared with diesel.
El-Kassaby and Nemit-Allah (2013) [43]	Four-stroke, single cylinder, direct injection, variable compression ratio diesel engine	• Compression Ratio (14, 16 and 18)	• Increase in Engine Torque for all blends at all compression ratios. • Increase in brake thermal efficiency and decrease in BSFC as the compression ratio increases. • Increase in NOx and CO_2 and decrease in CO and HC emissions as compression ratio increases. • Drop in Ignition Delay as compression ratio increases.
Hwang et al. (2014) [44]	Single Cylinder DI Diesel Engine	• Injection Pressure (80 MPa and 160 MPa) • Injection Timing (−25 to 0 CAD aTDC by 5 CAD).	• ISFC increases w.r. to Injection Timing for BD • Lower Peak cylinder pressure and the peak heat release rate for BD • Longer Ignition Delay for BD • CO, HC and Smoke get reduced while NOx increases.

Ahmed et al. [16] used Gas Chromatography analysis to derive and characterize the fatty acid composition of WCOME from Mustard Oil and used the same in a Mitsubishi Pajero engine to analyze the brake power as well as the emission characteristics. Mustard Oil biodiesel (MB) was proven to have superior oxidation stability and high calorific value among most of the biodiesels from different feedstocks. Significant reductions in HC and CO emissions and considerable noise reductions compared to pure diesel were recorded with the test fuel.

The performance and emission characteristics of WCOME depend upon the physiochemical properties of the fuel. The properties can be improvised by certain intensification technologies during the transesterification reaction itself. Waste cooking oil methyl esters produced by hydrodynamic cavitation technology were blended with pure diesel in different proportions, and their impact on the engine characteristics was studied by Chuah et al. [17]. 1.6%–6.7% lower brake power, 0.6%–5.2% lower torque and 1.9%–8.4% lower brake thermal efficiency were reported with the blends of WCOME as compared with pure diesel. The higher oxygen content of the biodiesel led to better combustion and hence carbon dioxide emissions were comparatively higher whereas the CO emissions were found to be lesser.

4. Study on the variation of Operating Parameters of the engine

More often, the properties of Petroleum based Diesel fuel determine the design and development of Diesel engines. Of late, vegetable oil-based biodiesels from different origins are being used in Diesel Engines. Hence, it becomes mandatory to study the choice of operating parameters of a Diesel Engine so as to make them suitable for use in diesel engines. The production technologies widely used for transesterification reaction also lead to many significant changes in the physiochemical properties of the resultant oil, which directly affect the operating parameters of the engine like injection pressure, injection timing, etc. Many researchers around the globe have worked on this objective. Table 4 shows the summary of such works wherein the operating parameters of the engine such as compression ratio, injection pressure or injection timing are varied to study the major characteristics of the engine.

The importance of sticking to the optimum compression ratio for the biodiesel driven CI engine, which is primarily designed to use diesel as its fuel, can be appreciated by varying the compression ratio through a given range and inferring the values of different operational parameters. Muralidharan and Vasudevan [45] studied the performance, emission and combustion of a variable compression ratio CI engine running with waste cooking oil methyl esters and its blends with standard diesel. Experiments were conducted at a fixed speed of 1500 rpm at 50% load and for different compression ratios of 18, 19, 20, 21 and 22. It was found that the brake thermal efficiency of the blend B40 was slightly higher than that of standard diesel at higher compression ratios, whereas the emissions of nitrogen oxides for the same blend of B40 are higher than that of the standard diesel. It was concluded that the performance of the B40 blend was superior when compared with the standard diesel at a compression ratio of 21.

Like compression ratio, the injection characteristics such as injection pressure and injection timing also play a major role in the combustion of CI engines. Kannan and Anand [42] varied the injection pressure and injection timing to determine the optimum working conditions for a single cylinder 4 stroke DI KIRLOSKAR diesel engine running with WCO as the fuel. Injection pressure was varied from 220 bar to 300 bar in the interval of 20 bar while injection timing was varied as 23° before Top Dead Center (bTDC), 25.5° bTDC and 28° bTDC. A combined setting of higher injection pressure of 280 bar as well as an advanced timing of 25.5° bTDC happened to be the optimum setting for the engine with biodiesel. An increase in BTE, reduction in emissions, rise in cylinder gas pressure and HRR were observed for the optimum setting.

Investigations have been carried out by El-Kassaby and Nemit-Allah [43], who intended to find out the impact of compression ratio and blending ratio on the combustion, performance and emission characteristics of a four-stroke, single cylinder, direct injection variable compression ratio diesel engine employing different blends of WCO biodiesel and diesel. Three different compression ratios such as 14, 16 and 18 and blends of B10, B20, B30, B50 were used for the experimentation. It is reported by the authors that with the increase in compression ratio, CO_2 and NO_x emissions went up by 14.28% and 36.84% respectively, whereas the HC and CO emis-

Table 5
Summary of works on ANN modeling with WCOME as the fuel.

Author (year)	Engine used	Input parameters of the network	Output parameters of the network	Key details	Highlights
Canakci et al. (2009) [52]	Water-cooled, four strokes and naturally aspirated Indirect injection Diesel Engine	• Engine speed • Fuel Properties • Environmental conditions	• Flow rates • Maximum injection pressure • Emissions • Engine load • Maximum cylinder gas pressure • Thermal efficiency	• Five different networks were tried. • Standard back propagation used as learning algorithm • Network with one hidden layer used	• The mean % error in the prediction of emission parameters was higher, whereas for others it is within the assumed limits • ANN model employed, produces R^2 value of 0.998508 and 0.992241 for the prediction of CO with training and testing data respectively. Similarly R^2 value of 0.999424 and 0.92668 for HC, 0.998216 and 0.995510 for NOx were reported for training and testing data respectively.
Ghobadian et al. (2009) [53]	Two cylinder four stroke diesel engine	• Engine speed • Blend percentage	• Torque • SFC • HC • CO	• Network with one to two hidden layers • Activation function used in the hidden layer is logsig • Standard back propagation used as learning algorithm	• MSE (Mean Square Error) error obtained as 0.0004. • The correlation coefficient values for training engine torque, SFC, CO and HC were found as 0.9999, 0.999, 0.9998 and 0.9999 respectively. The values are very close to 1, which is a clear indication of the predictions by the ANN model.
Shivakumar et al. (2011) [54]	Computerized 5.2 kW single cylinder, four stroke, naturally aspirated, direct injection, variable compression ratio, water cooled diesel engine test rig	• Compression Ratio • Injection Timing • Blend % • % of load	• BTE, BSFC and Exhaust Temperature (Performance Model) • NOx, Smoke and UBHC (Emission Model)	• Network with one hidden layer used • Activation function used in the hidden layer is tansigmoid • Standard back propagation used as learning algorithm • Performance of the model measured by Mean Relative Error (MRE)	• MRE was within the defined values of 5% and 8% for performance and emission models. • 96.6% and 93.3% prediction accuracies were recorded in predicting BTE for the training and testing data respectively, whereas proposed ANN Model predicted BSFC with an accuracy of 95% and 86.7% for the training and testing data respectively. The exhaust Temperature was predicted at 94% and 89.2% accurately for training data and the testing data.

sions decreased by 14.28% and 52% respectively. Increase in brake thermal efficiency was also recorded with the increase in compression ratio. The performance, combustion and emission parameters of a CI engine largely depend upon the pressure at which the fuel is injected into the chamber. Hwang et al. [44] analyzed the impact of injection parameters on the combustion and emission of single cylinder DI diesel Engine equipped with common rail injection system. The injection pressures used were 80 and 160 MPa while the injection timings were varied from −25 to 0 Crank Angle Degrees (CAD) after TDC in an increment of 5 CAD. The emission parameters such as HC, CO and smoke got reduced while using WCO, whereas NO_x increased with WCO for all testing conditions.

Salmani et al. [46] established a test set up to simulate hot surface temperatures and high ambient pressures inside the combustion chamber and compared the ignition delay characteristics of pure diesel and the micro emulsion of coconut oil at various conditions. The hot plate temperature was varied from 300 to 450 °C while the ambient air pressure was varied from 10 to 25 bar. At higher ambient air pressure of 25 bar, combustion characteristics for diesel and micro emulsion of coconut oil were nearly similar as both have approximately the same ignition delay at a fixed injection pressure.

5. Study on use of ANN modeling to predict key parameters of the engines

The advent of enhanced computing facilities has enabled many researchers to take advantage of computationally efficient numerical methods as well as intelligent tools to predict and optimize the operating parameters [47–51]. Artificial Neural Networks (ANN) is a modern modeling technique that allows one to predict the operating parameters with minimum experimentation in a much faster way with the help of the developed model. Many researchers have used this novel technique to predict and determine engine properties for different operating conditions which otherwise would have indulged in heavy investments. The review of such works has been discussed in the following section and tabulated in Table 5.

Canakci et al. [52] studied exhaustively the prediction of performance and emission parameters using five different neural networks. For all the networks, back-propagation algorithm was used. For the fifth network, the input parameters considered are engine speed, fuel properties and environmental conditions. Parameters such as flow rates, maximum injection pressure, emissions, engine load, maximum cylinder gas pressure, and thermal efficiency are assumed as the output parameters. The results showed a R^2 value of 0.99. Due to the complex nature of the combustion process, the mean % error in the prediction of emission parameters was higher whereas for others it is within the assumed limits.

Shivakumar et al. [54] conducted experiments on a single cylinder four stroke stationery, variable compression ratio DI diesel engine using WCO blends as fuel. Tests were carried out by varying the compression ratio as well as the injection timing. The author used the techniques of Artificial Neural Networks (ANN) to predict the performance and emission characteristics. Two separate models for the evaluation of performance and emission models were developed. Compression ratio, injection timing, load, blend percentage were used as input parameters. For the performance model, BTE, BSFC and Exhaust Temperature (T_{exh}) were used as output parameters, whereas for emission model NO_x, smoke and Unburned Hydrocarbons (UBHC) were used as output parameters. Reported results exhibit good correlation between predicted and experimental values. The Mean Relative Error (MRE) for the training data were 1.914%, 2.281% and 2.476% for BTE, BSEC, T_{exh} respectively, whereas for the test data these values were 1.929%, 3.064%, 3.109% respectively. Similarly, for the Emission Model, the MRE for the training data were found to be 3.864%, 5.105%, and 7.017% for the emissions of NOx, smoke and UBHC respectively, whereas for the test data they were 4.586%, 5.490%, and 7.342% respectively. Ghobadian et al. [53] employed a two cylinder Diesel engine to conduct experiments to evaluate the performance and emission characteristics. The author made use of the experimental results to develop an ANN model and predicted the performance and emission parameters quite accurately. Standard back-propagation algorithm was used for the model with the speed of the engine and the blend percentage as input parameters. The output parameters predicted were the engine torque, specific fuel consumption and the HC and CO emissions. The author employed one to two hidden layers and used logsig as the activation function for the hidden layer. The correlation coefficients (R) of the results were found as 0.9487, 0.999, 0.929 and 0.999 for the engine torque, SFC, CO and HC emissions, respectively.

6. Summary and concluding remarks

The various works related to the use of waste cooking oil methyl esters in compression ignition engines have been extensively reviewed and the key points have been tabulated. Based on the above review, the following concluding remarks can be drawn.

- The production technologies widely used for transesterification reaction lead to many significant changes in the physiochemical properties of the resultant oil, which play a major role in affecting the operating parameters of the engine. Various intensification technologies such as hydrodynamic cavitation and ultrasonic cavitation have been attempted to have high yield of methyl esters in minimum reaction time.
- Most of the researchers concluded that Brake Thermal Efficiency (BTE) and Indicated Mean Effective Pressure (IMEP) increased with the use of WCO biodiesel, whereas emission parameters like CO, CO_2, hydrocarbons were decreased.
- The common observation in most of the studies is the slight increase in the NOx emissions with the WCOME as the fuel. Brake specific fuel consumption (BSFC) was also found increasing due to the lower calorific value of the WCOME blends.
- The necessity to optimize the operating parameters of the CI engines that are designed originally to use diesel as the fuel has been emphasized with the help of the works carried out in this area.
- With its ability to predict the major performance, emission and combustion parameters of the engine without any prior knowledge of the process variables and with its versatility to accommodate multiple input and output variables, ANN modeling as one of the widely used techniques in the analysis of IC engines.
- Very minor error percentages were reported between the actual and the predicted parameter values in most of the research, which indicates the robustness and usefulness of the ANN models.
- It can be concluded that a lot more investigations need to be carried out in the area of reducing the NOx emissions as well as the in the optimization of operating parameters with WCOME using ANN and other optimization techniques. Such works in the future, which make use of the modern techniques of optimization, would definitely enhance the use of waste cooking oil methyl esters blends as a substitute for diesel in a much broader sense.

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